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X-rays from the Dawn of the Modern Universe. Chandra and XMM-Newton Observations of $z > 4$ Quasars

C. Vignali

INAF - Osservatorio Astronomico di Bologna, Via Ranzani 1, 40127 Bologna, Italy

W.N. Brandt, D.P. Schneider

Department of Astronomy & Astrophysics, The Pennsylvania State University, 525 Davey Lab, University Park, PA 16802, USA

Abstract. Quasars at $z > 4$ provide direct information on the first massive structures to form in the Universe. Recent ground-based optical surveys (e.g., the Sloan Digital Sky Survey) have discovered large numbers of high-redshift quasars, increasing the number of known quasars at $z > 4$ to ≈ 500. Most of these quasars are suitable for follow-up X-ray studies. Here we review X-ray studies of the highest redshift quasars, focusing on recent advances enabled largely by the capabilities of *Chandra* and XMM-*Newton*. Overall, analyses indicate that the X-ray emission and broad-band properties of high-redshift and local quasars are reasonably similar, once luminosity effects are taken into account. Thus, despite the strong changes in large-scale environment and quasar number density that have occurred from $z \approx 0$–6, individual quasar X-ray emission regions appear to evolve relatively little.

1. Introduction

Our knowledge of the X-ray properties of quasars at $z > 4$ has advanced rapidly over the past few years. In particular, the Sloan Digital Sky Survey (SDSS; e.g., York et al. 2000) has generated large and well-defined samples of $z > 4$ quasars (e.g., Anderson et al. 2001); most of these quasars are suitable for X-ray studies. The X-ray observational strategy has comprised archival studies of high-redshift quasars with *ROSAT* (Kaspi, Brandt, & Schneider 2000; Vignali et al. 2001, hereafter V01), snapshot ($\approx$ 4–10 ks) observations with *Chandra* to define basic quasar X-ray properties such as fluxes and luminosities (e.g., V01; Brandt et al. 2002, 2003; Bechtold et al. 2003; Vignali et al. 2003a,b, hereafter V03a, V03b) and longer observations with XMM-*Newton* to derive either tight constraints on the X-ray emission (e.g., Brandt et al. 2001) or spectral parameters by direct X-ray fitting (Ferrero & Brinkmann 2003; Grupe et al. 2004). *Chandra* snapshot observations have also allowed joint spectral fitting of subsamples of quasars drawn from two main samples at $z > 4$: the optically luminous Palomar Digital Sky Survey (e.g., Djorgovski et al. 1998) and the SDSS. The X-ray spectral results provide no evidence of strong spectral evolution

in radio-quiet quasar (RQQ) X-ray emission from local samples up to $z \approx 5$; the spectrum at high redshift is well parameterized by a power law in the $\approx$ 2–40 keV rest-frame band with $\Gamma = 1.8$–2 (V03a; V03b). Furthermore, no evidence for widespread intrinsic X-ray absorption has been found, although it seems likely that a few individual objects may be X-ray absorbed (e.g., V01; V03b). These overall results have been supported recently by direct X-ray spectroscopy of QSO 0000$-$263 at $z = 4.10$ with XMM-*Newton* (Ferrero & Brinkmann 2003).

The color selection of the SDSS has been proven to be effective in finding high-redshift optically luminous quasars up to $z \approx 5.7$ (see Fan et al. 2003 for SDSS quasars at higher redshifts). On the other hand, moderately deep *Chandra* observations and the ultra-deep (2 Ms) survey of the *Chandra* Deep Field-North (CDF-N; Alexander et al. 2003) can detect Active Galactic Nuclei (AGN) at $z > 4$ that are typically $\gtrsim$ 10–30 times less luminous than the SDSS quasars (e.g., Barger et al. 2002; Silverman et al. 2002; Vignali et al. 2002, hereafter V02; Castander et al. 2003). These AGN are much more numerous and therefore more representative of the AGN population at high redshift than the rare SDSS quasars; however, their X-ray emission does not appear to contribute significantly to reionization at $z \approx 6$ (Barger et al. 2003). A detailed X-ray spectral analysis of the $z > 4$ AGN in the CDF-N is presented in V02.

Below we present some new X-ray spectral results obtained by joint spectral fitting of all the RQQs at $z > 4$ thus far detected by *Chandra*. A spectral analysis performed on a smaller but more X-ray luminous sample of $z > 4$ radio-loud quasars is presented by Bassett et al. (in preparation).

2. Joint X-ray Spectral Results

To define the overall X-ray properties of $z > 4$ RQQs, we selected all of the RQQs detected by *Chandra* with > 2 counts in the observed 0.5–8 keV band. The sample comprises 46 quasars with a median redshift of 4.43; the number of source counts is ≈ 750. Note that these quasars represent a large fraction ($\approx 70\%$) of the optically selected RQQs at $z > 4$ with X-ray detections at present.[1] Although it is possible that individual objects are characterized by "peculiar" X-ray properties, our approach obtains average spectral parameters for the quasar population at $z > 4$ using a much larger sample than those presented in V03a and V03b. In the X-ray spectral analysis, the Cash statistic (Cash 1979) has been adopted. Our preliminary analysis shows that a power law fits the X-ray data reasonably well; the photon index in the rest-frame $\approx$ 2–40 keV band is $\Gamma = 1.9 \pm 0.1$ (see Fig. 1). This is consistent with previous results obtained for RQQ samples at high redshift observed with *Chandra* (V03a; V03b) and XMM-*Newton* (Ferrero & Brinkmann 2003; Grupe et al. 2004), as well as with quasar X-ray spectral results at low and intermediate redshift (e.g., George et al. 2000; Page et al 2003). Our analyses indicate that the X-ray spectral properties of $z > 4$ RQQs and local RQQs are similar; the only significant differences have been found in their broad-band properties using the

[1] See http://www.astro.psu.edu/users/niel/papers/highz-xray-detected.dat for a regularly updated listing of X-ray detections and sensitive upper limits at $z > 4$.

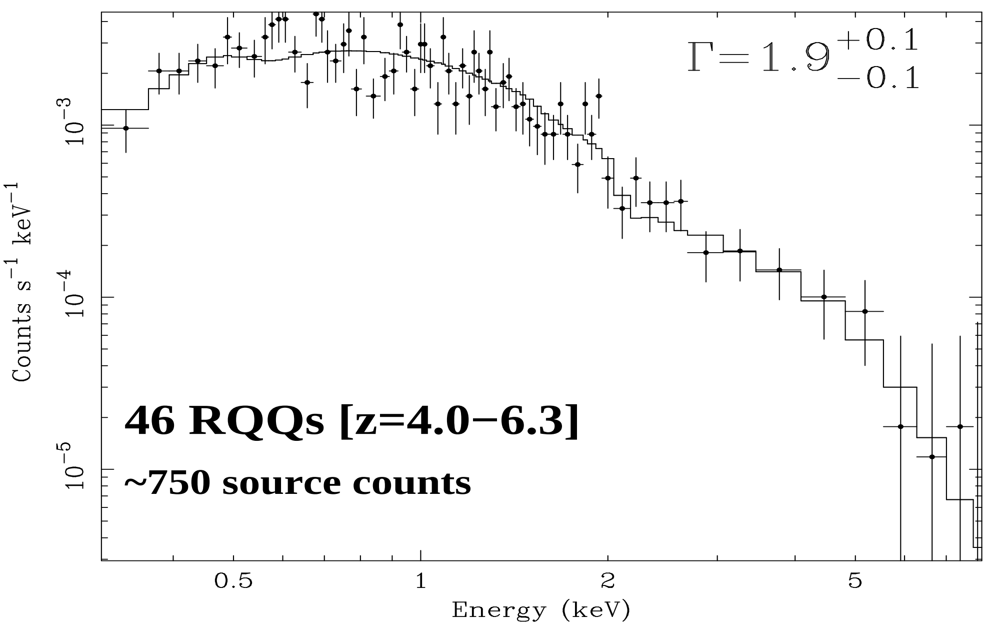

Figure 1. Combined spectrum of $z > 4$ RQQs detected by *Chandra* with > 2 counts in the observed 0.5–8 keV band. The spectrum shown here (only for presentation purposes) is fitted with a power-law model and Galactic absorption (see the text for details).

SDSS Early Data Release quasar catalog (Schneider et al. 2002) and are likely due to luminosity effects (Vignali, Brandt, & Schneider 2003; see also Brandt, Schneider, & Vignali, these proceedings). Thus, despite the strong changes in large-scale environment and quasar number density that have occurred from $z \approx 0$–6, individual quasar X-ray emission regions appear to evolve relatively little. From the joint X-ray spectral fitting we also find no significant evidence for absorption above the Galactic value; the upper limit in the source rest frame is $N_{\rm H} \lesssim 9 \times 10^{20}$ cm^{-2} (see Vignali et al., in preparation, for detailed discussion).

3. The Future

The correlation found between quasar AB magnitude at a rest-frame wavelength of 1450 Å and the observed 0.5–2 keV flux (e.g., V03b) is a powerful tool to select samples of $z > 4$ quasars suitable for follow-up X-ray observations. The combination of snapshot observations with *Chandra* and longer exposures with XMM-*Newton* should continue to be highly effective in allowing the study of the overall X-ray properties of quasars at high redshift. In the coming years, as the SDSS is completed and several thousand *Chandra* and XMM-*Newton* archival observations become available to the scientific community, our knowledge of the broad-band properties of quasars at the highest redshifts will significantly increase. However, detailed X-ray spectroscopic analyses of large samples of $z > 4$ quasars must await the more distant future and X-ray missions such as *Constellation-X*, *XEUS*, and *Generation-X*.

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